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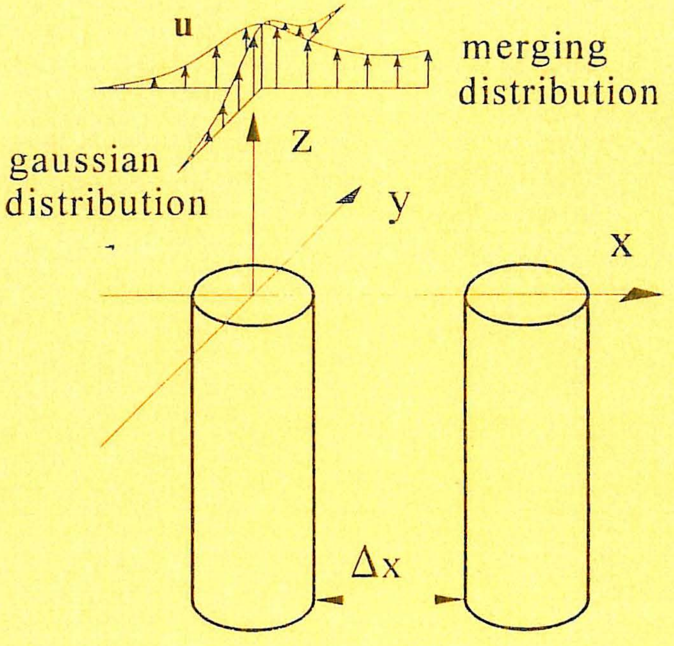

INDOOR ENVIRONMENTAL TECHNOLOGY
PAPER NO. 54

Presented at Healthy Buildings '95
Milano, Italy, September 1995

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INTRODUCTION

Today, it is possible to calculate the contaminant distribution reasonably well in rooms with steady flow, with a known contaminant emission, and without people. People have a complex influence on the indoor environment, as they are heat and contaminant sources, and act as mobile flow obstacles with complicated geometry. The air velocities and temperatures in the immediate surroundings of a human being, i.e. in the boundary layer flow around the body and in the plume above it, bear large influence on the dispersal of heat and bioeffluents from the body, as well as on the total flow field in a room.

OBJECTIVES

This experimental work deals with the basic problem of merging thermal plumes from heat sources situated in the vicinity of each other. No studies have been made yet of how close two heat sources must be to each other, before they can be considered as a single source with a cumulative heat effect, and how far apart they must be to be considered separate. Also, it is not known how the flow field behaves in the intermediate fase, where the plumes are neither completely joined nor completely separate. A possible, very simple, solution of the velocity distribution between two plumes is to assume addition of the velocities from each plume (see Figure 1). This solution has been used in another context as a boundary condition for numerical simulations of buoyant jets (Davidson et.al.,1994). The main objective of this research is to compare this assumed distribution with measurements made in a full scale experiment with typical room air temperatures and with heat sources similar to human beings.

The buoyant plume over a single heat source is described thoroughly in previous work (e.g. Morton et.al.,1956). Analytical results have been obtained from studies of the plume from a point source. The ambient vertical temperature gradient is an important parameter, as the flow loses its buoyancy when the ambient temperature equals the plume temperature. The experiments described in this paper concentrate on the simplest possible situation, namely uniform ambient temperature. At a certain height, the plume from an extensive source like a person is similar to that of a point source placed at a "virtual origin" (Figure 1). However, close to the heat source, the plume is not fully developed, and there is a transistion zone, where the flow changes from a boundary layer flow to a buoyant plume (Kofoed and Nielsen, 1990).

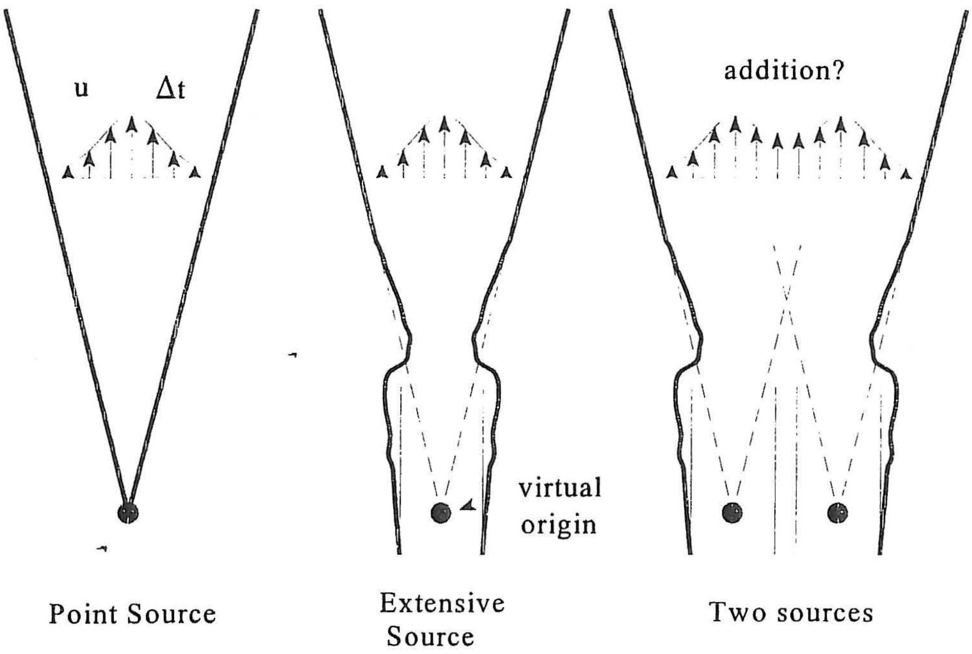

Figure 1. The velocity (u) and temperature (Δt) distribution in a plume above a heat source with uniform ambient air temperature.

METHODS

Full-scale experiments were carried out in a climate chamber, using a very simple physical model of a human being as heat source. The heat source was a steel cylinder (painted in a dull black colour) with surface areas and heat output corresponding to a human being (Diameter = 0.4 m, Height = 1.0 m, Total heat effect = 100 W). Two such heat sources were placed in varying distances (0.0 m, 0.1 m, 0.3 m, 0.5 m, 0.8 m, 1.1 m) from each other, and air velocities and temperatures were measured in the range of 0.75 m - 2.5 m above one of the sources with an interval of 0.25 m. Measurements were also made with only one source present. The air velocities were measured with hot sphere anemometers together with a data processing device (both of the type Dantec 54N10 MFA), calibrated to an accuracy of $\pm$ 0.01 m/s in the range of 0.0 -1.0 m/s. The sampling time for each measurement was 25 min. Temperatures were measured with thermocouples (type K) and a data logger (type Fluke Helios 2287 A) connected to a PC. The thermocouples were calibrated to an accuracy of $\pm$ 0.15°C in the range of 10-30°C. The interior surface temperatures of the chamber as well as the room air temperatures were measured at several heights. The mean air temperature during the experiments was 20°C $\pm$ 0.5°C. The vertical temperature gradient in the chamber was less than 0.025°C/m.The surface temperatures were very close to the mean air temperature.

An important problem, which must be considered with respect to the experimental methods, is the meandering of the plume axis.The anemometers were arranged in a cross pattern with 12 anemometers placed symmetrically a round the source in the x-direction (See Figure 2), with 0.1 m spacing, and 12 anemometers were placed similarly in the y-direction. Temperatures were measured at the same locations. By measuring in this cross pattern, it was possible to keep track of the plume meandering.

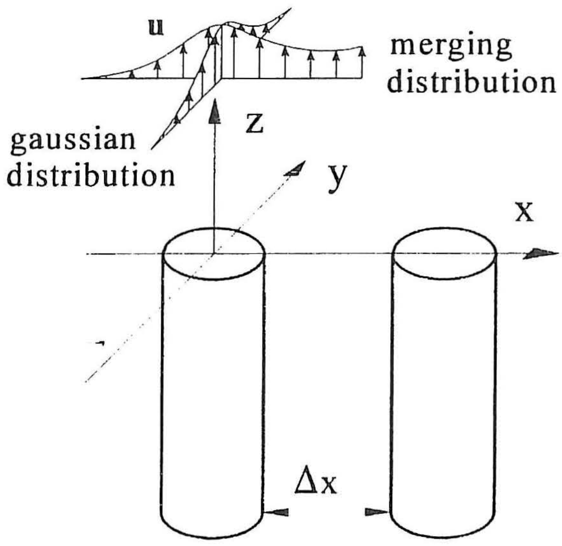

Figure 2. Schematic representation of the heat sources, coordinate system and expected velocity distribution.

RESULTS

First a single plume is investigated, partly to make comparisons with previous work with a similar experimental setup (Kofoed and Nielsen, 1990), partly to establish the "design" parameters to be used in the theoretical calculations of two merging plumes. The measurements (See figures 3 & 4) agree quite well. When the spread angle is slightly larger in the present experiment, and the velocities slightly lower, it is due to larger sampling periods, which "evens out" extremes. The design parameters: plume radius R_u, maximum velocity u_{max}, and virtual source location z_0, are found. The plume radius R_u is defined as the radius where the velocity is $1/e$ of u_{max}.

$$R_u = 0.139\ z + 0.146 \tag{1}$$

$$u_{max} = 0.304 \cdot (z + z_0)^{-0.390} \tag{2}$$

$$z_0 = -1.05\ m \tag{3}$$

The velocity profile at given distance r from the plume axis and at at given height z from the heat source can be calculated assuming a gaussian distribution:

$$u / u_{max} = exp (- r / R_u) \tag{4}$$

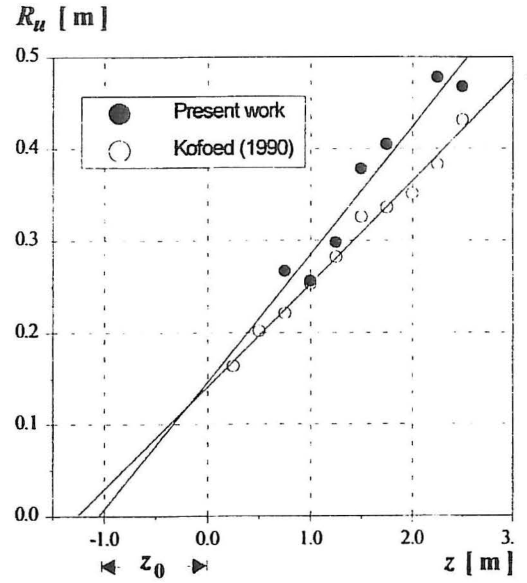

Figure 3. Velocity radii of single plume

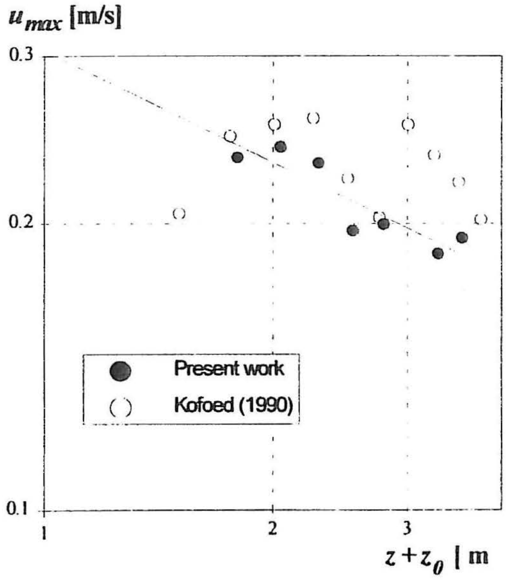

Figure 4. Velocity decay of single plume.

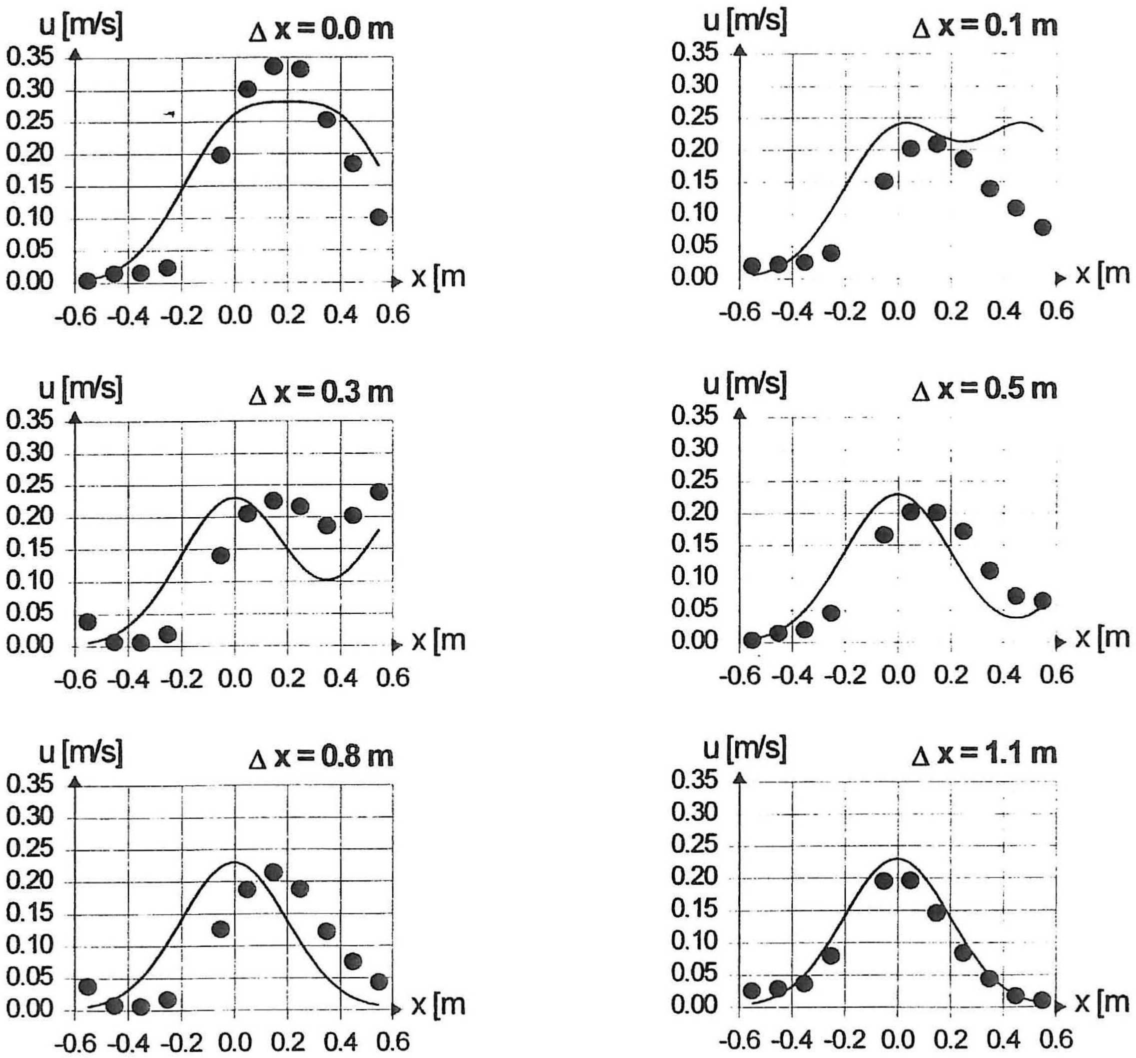

Figure 5. Velocities (●) measured at z = 1.0 m compared to the addition hypothesis.

Velocity profiles measured over two heat sources are shown for the constant height z = 1.0 m (Fig. 5). The location of the plume axis is shown for the x-axis in figure 6. The velocity distribution is always symmetrical around y = 0 on the y -axis.

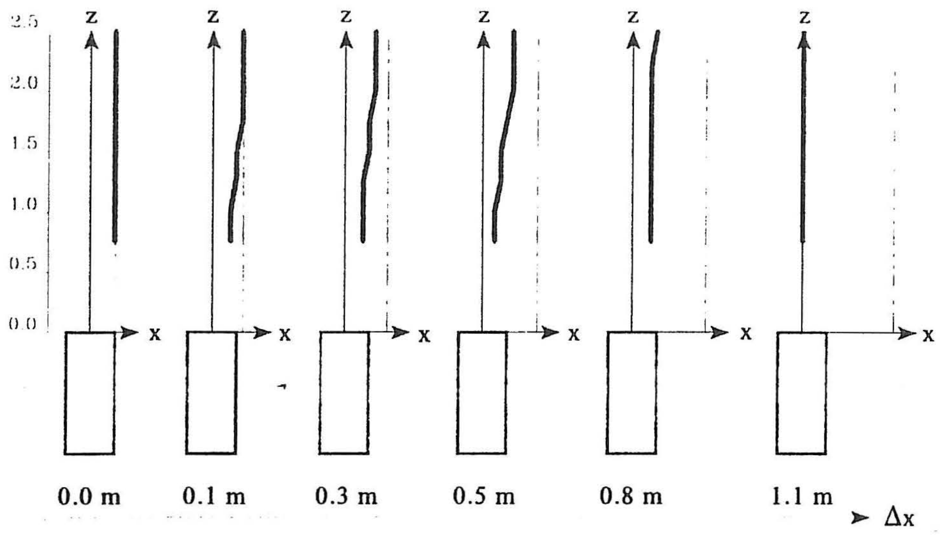

Figure 6. Displacement of plume axis. The dashed line represents the symmetry plane between two heat sources. The thick line represents the plume axis.

DISCUSSION

By assuming an axisymmetric, gaussian distribution of velocities, it is possible to find maximum velocities, volume flux, and energy flux in a single plume by using an extrapolation method (see Kofoed and Nielsen, 1990). In the case of two or more heat sources with merging plumes, neither of the assumptions hold. When the plumes of two or more heat sources merge into each other, the velocity distribution changes from a axisymmetric, gaussian distribution to a "merging" distribution. The absence of axisymmetric flow renders the extrapolation method impossible, which constitutes an important experimental problem to be dealt with. This was done by chosing a rather large sampling time (25 min) to eliminate most of the influence from the plume "meandering". In this way, the velocities measured along the x-axis were quite good approximations to the maximum mean velocities. However, it is not possible to calculate the volume flux etc. from these measurements.

Measurements are only shown for a fixed height of z = 1.0 m over the heat sources. At this height, the addition hypothesis yeilds reasonable results for distances larger than approx. 0.3 m.(See figure 5). At smaller distances, the hypothesis is less convincing, but is still much better than might be expected. At distances $\Delta x = 0.0$ m and$\Delta x = 0.1$ m, the plumes act as a single plume, however, the velocity level is dramatically reduced at $\Delta x = 0.1$ m compared to $\Delta x = 0.0$ m. At $\Delta x = 0.3$ m, the plumes begin acting as two seperate plumes with a merging velocity distribution. At $\Delta x = 1.1$m, the velocity distribution is completely unaffected by the presence of another heat source. At the height z = 0.75 m, there is larger discrepancy between measurements and the addition hypothesis. This is probably due to the plumes not being fully developed yet at this height. At heights of z > 1.0 m, the picture is much the same as described above.

One may conclude, that the heat sources must be in actual physical contact to be considered as a single heat source with cumulative effect. Even a small distance between them alters the velocities significantly. The heat sources can be considered separate when the distance between them exceeds approx. 1m.

There are two major reasons for the deviations between the hypothetical curves and the measurements. One is the fact that two heat sources placed very close ($\Delta x \leq 0.1$ m) generate a single plume rather than two interacting plumes. The other reason is the deflection of the plume axis from the centre of the heat sources. This phenomenon is similar to the coanda effect. The observations are illustrated in figure 6. The plumes are only completely joined at all heights when the distance between the heat sources is zero. The coanda-like effect is quite obvious until $\Delta x = 1.1$ m, where it suddenly disappears completely.

This work is part of ongoing efforts to create a CFD (Computational Fluid Dynamics) model which describes the transport processes governing the dispersal of airborne pollutants in buildings, and to validate this numerical model by full-scale experiments. Usually in CFD simulations, the velocity and temperature fields are calculated first and used to calculate the concentration distribution. An important issue is the question of boundary conditions. In the case of buoyant plumes from heat sources, a possible way of setting the boundary conditions would be to prescribe a velocity, a temperature, and a concentration distribution close to the source. The idea of using the principle of addition seems to be promising, and further investigations will be made.

ACKNOWLEDGEMENTS

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